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ELECTRON-OPTICAL EFFECTS IN THE DEVELOPMENT OF PLASMA

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/Figures are appended/

Introduction and Statement of Problem

In a series of projects in our laboratories on the study of discharges in a magnetic field, we limited ourselves to the study of the plasma /1/ and the anode part of a stationary discharge. The essential difference between the plasma developing and that already formed, from the viewpoint of electron optics, is that in the electrons, there is a difference in the velocity-distribution function. During ignition of the discharge, a directed motion of the high-speed electrons is sharply evident. As is known, X-rays are generated on the anode in the initial phase, which is positive proof of the highly-directional velocities of the electrons during spark-over /2/. In stationary plasma, the electrons have basically a thermal Maxwellian distribution by velocities with a small drift along the axis of the discharge. It is natural, therefore, to expect that with the action of the magnetic lens on the plasma which is developing, there should arise specific focusing effects of the concentrated, axial, symmetrical, magnetic field which are much stronger than in stationary plasma. In the light of this problem, a systematic study of the influence of magnetic fields of various configuration on the development of discharges in long tubes was undertaken.

The theoretical significance of the problem is established by the fact that theories describing all phases of the development of the discharges in long-discharge gaps do not exist for low pressures at present. It is true that questions dealing with the ignition of gas discharges have had many experimental and theoretical studies devoted to them, but they all pertain either to the problem of ignition of short discharge gaps, or do not deal with the specific electron-optical mechanisms which appear in the spark-over of long gaps in systems having axial symmetry. The usual limiting conditions assume that the discharge takes place between flat, parallel, infinite electrodes, between two infinite cylinders, etc. The

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walls enclosing the long-discharge gaps not only have the function of enclosing the surfaces on which the escape of ions and electrons takes place, but also actively participate in the electrical and energy balance of the discharge.

There are only a few studies dealing with the ignition of discharges in long-discharge gaps. The dependence of the ignition potential on the radius of the tube for neon, silver, helium, and air was found experimentally [3]. Quantitative and qualitative data on ignition columns was given in the works of Mierdel and Steenbeck [4], Bartholomyezyk [5, 6], Seeliger and Bock [7]. The basic idea in the work of Mierdel and Steenbeck is that the electron, during its existence, i.e., until it reaches the walls, should generate its substitute.

Steenbeck derives the ignition conditions for limited discharge

$$\gamma \frac{\alpha}{\alpha'}\left(e^{\alpha' d} - 1\right) = 1,$$

where

$$\alpha' = \alpha - \frac{1}{L}. \qquad (1)$$

The term $\frac{1}{L} = \frac{1}{L_+} + \frac{1}{L_-}$ characterizes the losses of charged particles per unit length of the path. L_- represents the section of the path traversed by an electron in the direction of the field; L_+ is the section of the path traversed by an ion in the direction of the field; α is the coefficient of volumetric ionization of the electrons; γ is the coefficient of surface ionization of the ions, and d is the distance between the electrodes.

However, it should be noted that Steenbeck's expression relates essentially to the moment when the static column is established in the presence of an already existing longitudinal field, formed by charges which cover the walls uniformly. The problem of how the field in the column was created and how the charge on the walls was formed lies outside Mierdel's and Steenbeck's theory. Seeliger and Bock, examining diffusion equations in corresponding conditions (low pressures and long gaps), showed that practically no electron can penetrate a distance further than the radius of the tube, from the place of its origin in the direction of the field.

Further, in deriving the ignition conditions, Mierdel and Steenbeck concluded that all secondary processes lead to the extraction of electrons from the cathode surface by the ions, i.e., they did not take into account the part played by charged particles originating as a result of photoionization in the gaseous space and on the cathode surface. Finally, they considered as constant the coefficients α and γ which are functions of time alone, and completely ignored the role played by the space charges originating in the gap which distort the field distribution.

Bartholomyezyk, basing his work on Mierdel's and Steenbeck's ideas, further developed them. He introduced a time factor in the integration of the particle-balance equations, taking into account the diffusion on the walls. The calculation of the boundary conditions gives a generalization of the ignition conditions in the form

$$\gamma \int_0^d \alpha e^{\int_0^x \left[\alpha - \frac{2 \cdot 4^2}{R^2}\left(\frac{D_+}{v_+} + \frac{D_-}{v_-}\right) - \frac{h}{v}\right] dx} dx = 1, \qquad (2)$$

which, for a uniform field (α = const) and a stationarily burning discharge, changes to the Mierdel-Steenbeck conditions.

In addition, Bartholomyezyk attempted to calculate the role of photoionization on the cathode and concluded that this photoionization should grow with an increase of the gap length d. It is necessary to point out that a principal difference exists between Bartholomyezyk's time constant and the actual time of the formation of the discharge. He did not consider the part played by the field on the walls, whose charge gradually becomes constant longitudinally, nor the distortions of the field

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introduced by the space charges of the ions during ignition, etc. Since, during ignition, we are dealing with a directed movement of charged particles in an axial-symmetrical system, i.e., the discharge tube, it is convenient to examine the phenomenon as an electron-optical problem. To demonstrate our supposition, an iron-clad magnetic lens with an air gap was selected. The ignition potential was selected as the criterion of the influence of the lens field on the development of the discharge.

Magnetic Lens and Tube

Measurement of the lens field showed that it extends far beyond the limits of the lens gap. This is connected with the internal diameter of the lens -- 65 millimeters. The width of the lens was 66 millimeters and the width of the gap was 5 millimeters. The lens was fastened to an optical bench and was freely movable on the measuring tube. The construction of the measuring tube was very simple. The cathode was securely fastened on the axis in a slide which permitted change to other forms of electrodes. The anode was a round-edged flat disc with a diameter of 12 millimeters. The anode could be freely shifted by using the magnet and, in the same way, the length of the discharge gap could be changed from 93 to 150 millimeters. The diameter of the tube was 20 millimeters. The tube construction satisfied the following condition: the length of the gap was considerably greater than its diameter. The measurements were made in neon in a pressure interval of 0.1 to 0.6 millimeters.

Action of Magnetic Lens During Spark-Over in Cathode Sections of Discharge

The lens was placed on the tube so that the discharge point was located exactly at the edge of the lens. The distance from the point (cathode) to the center of the gap was 33 millimeters. This distance remained constant so that the location of the lens did not change the velocity of the electrons, i.e., taking one of the curves, the initial velocity of the electrons on entering the lens was almost constant. The first series of curves was taken at a pressure p equals 0.14 millimeters of mercury. Since the curves giving the relationship between the ignition potential V_z and I (current in the coil) were nearly parabolas, then the curves V_z were plotted as functions of I^2.

Figure 1 shows that for a distance in which d equals 95 and d equals 130 millimeters, a reasonably straight-line relationship is obtained. A dip is seen in the third curve. The straight-line parts of all three curves have about the same slope α, at which $tg\alpha$ equals 150 V/A^2. At higher pressures (p equals 0.26 millimeters of mercury and p equals 0.32 millimeters of mercury) the dips are not found on the parabolas, and linearity was more clearly evident, (Figure 2). The slope is still the same. In the change to lower pressures, the symmetrical dips become deeper and more abrupt; and as the distance between the lens and anode is increased, the dips are shifted toward the area of weaker currents (Figure 3). Thus, with this series of observations, certain conclusions can be drawn.

The ignition potential V_z is a function of the nature of the electron motion. The lens, forming the initial electron beam, decreases the losses of charged particles on the walls and increases the efficiency of each particle by directing it along a more favorable path. The action of the lens facilitates the establishment of a galvanic connection between the cathode and anode, which should exist in the first phase of the development of the plasma. Both effects must be connected with the optical power of the magnetic lens.

Since $H \sim I$, then $\frac{1}{f} = kI^2$ and, consequently, $V_z = \varphi(I^2)$, i.e. it will be a certain function of I^2. Tests show that under certain conditions this is actually so.

The factors entering into φ are the parameters of the coil, velocity of the electrons (the relationship $\frac{e}{m}$). In addition, allowance is made for collisions since the magnetic lens formula is correct for electrons not sustaining collisions. The phenomenon of electron-optical mechanisms is astonishing at such relatively

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high pressures as tenths of millimeters. The explanation for this is that during spark-over there is a sharp indication of directed electron motion.

If we evaluate the free path length of the electron, then it is found that the dip on the curves appears at pressures when the length of the free path is equal to the radius of the tube. It is possible that the fastest electrons from the discharge point can strike the wall and, charging the wall negatively, form a ring of negative charges on it which can be regarded as an additional electrical lens (Venel't's cylinder). This lens causes the dip effect on the parabolas. Additional decrease of the ignition potential is thus associated with an additional electrical focusing of the electron current from the discharge point to the anode. Thus, at high pressures, only the magnetic lens operates; at low pressures, both the magnetic and electrical lenses.

Change in Ignition Potential as a Function of Distance Between Anode and Lens

It is obvious that electron-optical mechanisms can be demonstrated through the periodic change in ignition potential.

A change in the form of the curves, depending on the anode position, and also considerations of the relative presence of a focusing region, show that, in analyzing V_z equals f(d) with the location of the anode at a distance corresponding to the focal distance of the lens, a certain minimum ignition potential should be observed. This will occur when the greatest number of electron paths end on the anode. Figure 4 gives the dependence of the ignition potential on the distance between the cathode and anode for various currents in the coil. The pressure p equals 0.14 millimeters of mercury. On all the curves there can be found two minimum points and one maximum. Thus, the curves show a certain periodic change.

Ignition With Magnetic Lens Shifted From Cathode

The magnetic lens is placed 63 millimeters from the cathode. The distance between the anode and cathode can be changed from 93 to 150 millimeters. A point cathode is used, while the anode is a flat disc with a diameter of 12 millimeters. The results of the measurements are shown by the curves of Figure 5. Attention is called to the dips which are less pronounced for the weaker currents in the lens. Periodic increases and decreases of the ignition potential, with a change in lens current, can be explained by the fact that the focusing area is shifted relative to the anode. This can be directly observed if the current in the lens is taken as a parameter and the anode is shifted. Figure 6 represents this case, showing the sharply expressed periodic change of the ignition potential. The curves of the dependence of ΔV_z on d are represented in Figure 7, but they were obtained in a different way. Here, each point was taken as the difference between the ignition potential without a field and with a field for a given position of the anode d.

It is clear from Figures 6 and 7 that, with an increase of the magnetic field, the amplitudes of the oscillations in ignition potential are increased, while the period decreases. The picture obtained becomes understandable if we keep in mind that the internal lens diameter is 65 millimeters and, consequently, the field extends beyond the limits of the lens in both directions.

It is interesting to compare the influence of the magnetic lens when located at the cathode and at the plasma region. If the lens is located at the cathode, the electrons immediately fall into the strongly concentrated field of the lens, and, therefore, even small currents in the lens have a sufficiently strong influence on the electron trajectories. As a result, the curves have a correct form. In the second case, since the electrons coming from the direction of the cathode fall into a comparatively weak dispersion field, small lens currents have little effect on the formation of the initial electron beam and, consequently, on the change of the ignition potential. Besides this, the beam falling into the lens field should be less concentrated due to the great distance from the cathode.

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It appears to us that the periodic change in the ignition potential is typical of electron-optical effects and is associated with the kinetics of electrons in the lens field in the presence of the drift velocity. From the increase in amplitude ΔV_z as H is increased, it is easy to understand that the stronger the field, the greater the effect. The periodicity in the space is connected with the periodic focusing of electrons on section z, which leads to the appearance of a corresponding periodicity in the ignition potential

$$z = \frac{2\pi mc}{eH} \bar{v} \cos\alpha, \tag{3}$$

where $\bar{v}\cos\alpha$ is the drift velocity along the axis of the tube. By substituting the drift velocity in place of the actual velocity, we allowed for collisions to some extent. If the longitudinal magnetic field is decreased, then the distance between the maxima of the ignition potentials is increased. This can be seen by comparing Figures 4 and 6. Actually, the intervals between maxima increase according to increasing distances from the lens. A clearer periodic change in ignition can be found in a uniform longitudinal field.

Influence of Uniform Magnetic Field on Ignition Potential

If the expressed considerations are correct, then the periodic change of the ignition potential should also be observed in the longitudinal field of a long coil by moving the anode along the axis of the tube.

The distance between the cathode (point) and anode (disc) was adjustable from 75 to 135 millimeters. The coil, 600 millimeters long with a diameter of 80 millimeters, was moved along the tube so that the cathode was located within the coil at a distance of 60 millimeters from the edge. The results of the measurements are given in Figure 8, where the curves show the dependence of the ignition potential on the coil current, with d serving as a parameter, and in Figure 9a where the curves represent the dependence of the difference in ignition potentials with and without a magnetic field (ΔV_z) on d (with coil current serving as the parameter). While the strength of the current in the coil is small (3-4 amperes), the ignition potential does not change significantly. A particularly abrupt drop of the ignition potential is found for currents of 5-6 amperes, which corresponds to a field of about 90 gausses (when I equals 6 amperes, H equals 87 gausses).

A further increase of the field to 145 gausses, corresponding to a coil current I equals 10 amperes, does not lead to any further substantial decrease in ignition potential. On the other hand, there is found a distinctly expressed periodic change in the ignition potentials at these currents. Therefore, if z is determined for several currents in the coil and the curve $z(\frac{1}{I})$ is constructed, or what amounts to the same, $z(\frac{1}{H})$, then a linear relationship is obtained, as was expected (Figure 9b). The drift velocity, according to Raether /8/ for p equals 760 millimeters of mercury and E equals 31,600 volts per centimeter equals

$v_d = 2 \times 10^7$ centimeters per second.

Considering that v_d equals $f(\frac{E}{p})$, the drift velocity of the electrons can be evaluated roughly for ignition under our conditions. Considering that the potential drop along the tube is uniform, we get E equals 42 volts per centimeter and p equals 0.1 millimeters of mercury.

Then, $v_d = \frac{2 \times 10^7 \times 7600}{760} = 2 \times 10^8$ centimeters per second.

Placing this value of the drift velocity of the electrons into the formula for the ignition potential period, an approximate value can be obtained for the ratio $\frac{e}{m}$ and it is possible to quantitatively verify the concept of the connection between ignition potential and electron focusing.

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For a field H equals 145 gausses, z equals 1.7 centimeters. Substituting in formula (3), we get

$$\frac{e}{m} = 0.2 \times 10^{18}.$$

The order of magnitude is correct, despite the very rough approximation.

Magnetic Lens in Anode Sections of Discharge

The measurements were taken in a tube with the cathode in the shape of a flat disc with rounded edges and a diameter of 12 millimeters. The anode was a hollow cylinder 60 millimeters long, having a diameter of 6 millimeters.

The magnetic lens was fixed on the tube in such a way that the whole anode could be shifted into the concentrated lens field. The distance between the electrodes varied from 35 to 60 millimeters by moving the cathode with the help of a magnet. The curves of the dependence of V_z on the lens current I are given in Figures 10 and 11. When the pressure is sufficiently large (Figure 10), the ignition potential increases with an increase in the magnetic field. This is clearly a result of the hampering effect on the electrons falling into the anode (a decrease in the probe currents occurs for this same reason), in a direction perpendicular to the magnetic field.

At lower pressures, (Figure 11), the ignition potential at first decreases only for large lens currents. At a pressure p equals 0.15 millimeters, the ignition potential for all currents in the presence of a field is no higher than the ignition potential without a field. Characteristic humps are noticeable on the curves which indicate a certain tendency to increase the ignition potential. Obviously, here are the combination of two effects: the effect discussed above where the mutually perpendicular electrical field and the magnetic field of the lens are combined, and the second effect of the focusing of the electrons (electron-optical effect). If we plot the curve showing the dependence of ΔV_z on I/p in order to detect the exact moment when the ignition potential changes from an increasing to a decreasing function, then it will be apparent that the change occurs suddenly. This change can be related to the ignition of the original plasma at the anode surface (strengthened ionization in the region of the anode drop).

When the pressure is lowered, the runs increase and the electrons begin to ionize actively at the surface of the anode and form additional plasma. From this moment, the d effect almost does not hinder the focusing action of the lens.

A similar picture is obtained with these same electrodes if a tube is placed in the long coil. It is clear from Figure 12, that here also, as the field is strengthened, the ignition potential at first increases, and then drops suddenly with currents in the coil of 5-6 amperes (H equals 80-90 gausses). This can be explained, as in the previous case, by the rise of active plasma at the anode.

Conclusions

1. Investigations were conducted on the influence of a concentrated magnetic field (the field of a magnetic lens) on the development of a discharge in an axially-symmetrical system -- a long cylindrical tube with a point source of electrons (point cathode).

2. It was shown that, under the examined conditions, there exists a definite relationship between the laws of electron optics and the development of a gaseous discharge: (a) the ignition potential is approximately a quadratic function of I^2 which indicates the connection with the magnetic lens formula; (b) the periodic change of the ignition potential was determined and an interpretation given of this effect as being a periodic focusing of electrons.

3. The calculated $\frac{e}{m}$ obtained from these considerations was of the correct order of magnitude.

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4. The noticeable focusing of electrons in definite places along the discharge gap is facilitated, during ignition of the discharge, by the fact that the electron motion in this phase of the discharge has a highly directional character.

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/Appended figures follow./

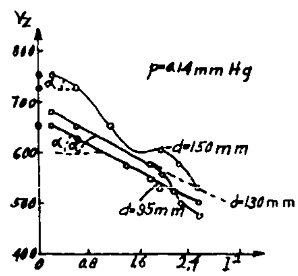
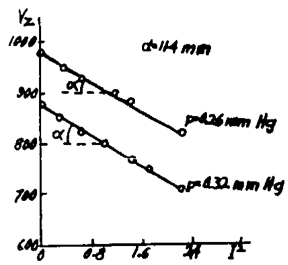


Figure 1



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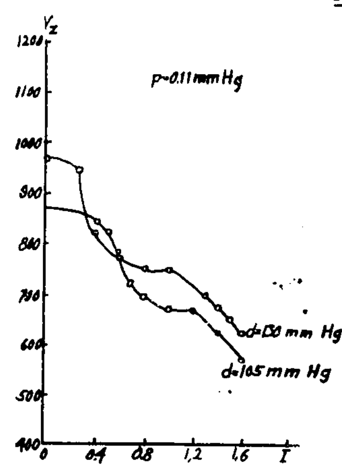

Figure 3

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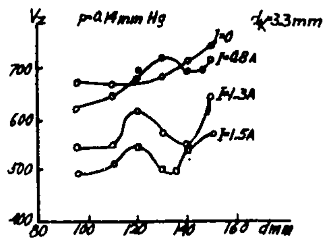

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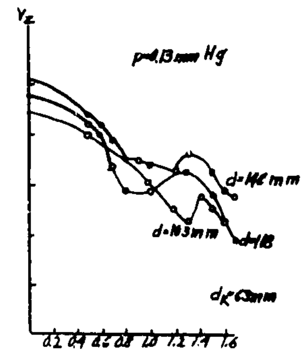

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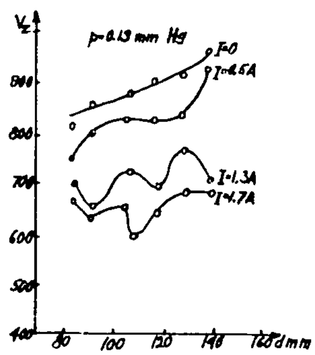

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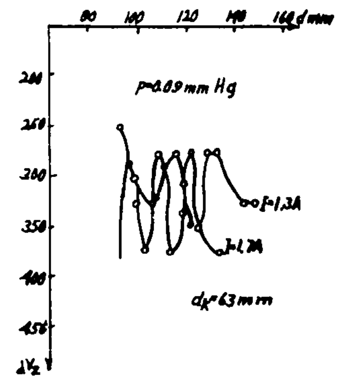

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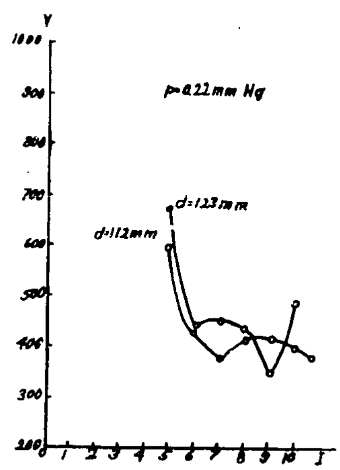

Figure 8

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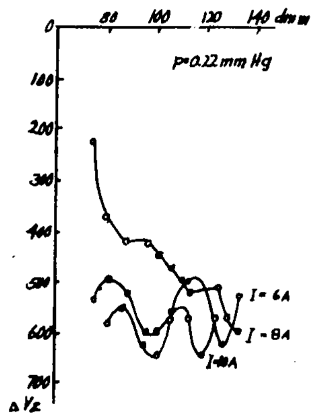


Figure 9a

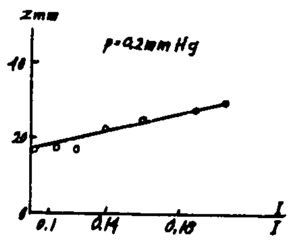


Figure 9b

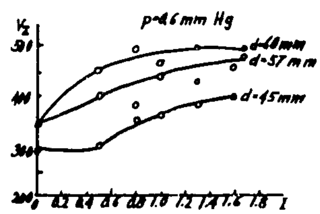
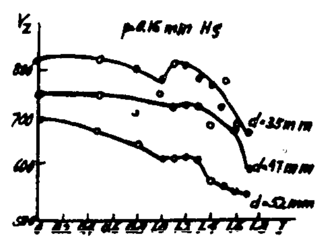


Figure 10



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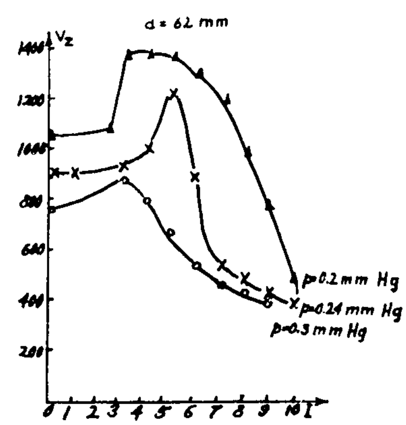

Figure 12

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